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ABSTRACT

The goal of this paper is to sketch the epistemological roots of constructivism, to clarify certain implications of Piaget's constructivist theory for science education, and to explicate the issues surrounding a specific research study and its replication. Constructivist epistemology is described in terms of its emergence from rationalist, empiricist, and romanticist views of knowledge. Implications for science teaching are derived from Piaget's descriptions of social, physical, and logico-mathematical experiences as sources of knowledge. A study which exemplifies the confusion surrounding constructivism is then discussed. Support is given for the use of discovery methods on the grounds that they foster the construction of logico-mathematical knowledge better than do more direct methods. Twenty-seven references are provided. (Author/ML)

The Constructivist Epistomology of Jean Piaget:

Its Philosophical Roots and Relevance to Science Teaching and Learning

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Abstract

The goal of this paper is to sketch the epistomological roots of constructivism, to clarify certain implications of Piaget's constructivist theory for science education, and to explicate the issues surrounding a specific research study and its replication. Constructivist epistomology is described in terms of its emergence from rationalist, empiricist, and romanticist views of knowledge. Implications for science teaching are derived from Piaget's descriptions of social, physical, and logico-mathmatico experiences as sources of knowledge. A study which exemplifies the confusion surrounding constructivism is then discussed. Finally, a concluding thought is presented.

Constructivist Epistomology of Jean Piaget: Its Philosophical Roots and Relevance to Science Teaching and Learning

Introduction

Perhaps the single reason that Piaget's theory remains attractive after nearly thirty years of study by the science education community is his delineation of a formal operational period of intellectual development, one in which an individual displays abstract thinking in general and specifically such capabilities as control of variables, proportional, hypothetico-deductive, and combinatorial reasoning. The presence or absence of such reasoning is a key in Inhelder and Piaget's (1958) descriptions of sujects' thinking about problems of bending rods, pendulum oscillation, chemical combinations, and balance equilibrium. Clearly, formal thought and the reasoning contained therein are relevant to science teaching and learning since formal thought is reasoning used in science itself.

Early on, we viewed the application of Piagetian theory to science teaching and learning in rather simplistic terms. Our job was to teach students to use formal reasoning patterns, to move them into Piaget's formal operational period as quickly as possible. It was not surprising to find that elementary school children do not yet use formal reasoning. But it was surprising to discover that large percentages of adolescents in junior high school through college often do not use formal reasoning in science classrooms (e.g., Chiappetta, 1976; Howe & Durr, 1982; Lawson, 1982; Staver, 1984; Staver & Gabel, 1979; Staver & Halsted, 1982; Staver & Pascarella, 1984). And it was even more surprising to some that such adolescents could not be quickly and permanently accelerated into formal operations (e.g., Lawson, 1985; Greenbowe, Herron, Lucas, Nurrenbern, Staver & Ward, 1981).

The acceleration issue, known as the American question, represents a fundamental error of interpretation. We tried valiantly to pour knowledge into youngsters' heads in the great empiricist tradition. In so doing, we have come to realize that the kind of knowledge described by Piaget is acquired in a very different way. It is constructed by children from previous knowledge and their interactions with the environment.

Perhaps the error stems from our desire for a quick, easy solution. The science education community acquired a severe case of tunnel vision, in that it focused its efforts on the stage concept of Piagetian theory, which contained clear applications for science teaching and learning, and overlooked more important, fundamental aspects. According to Kamii (1983), a noted Piagetian scholar, three ideas which are wider in scope than the stage concept and heretofore largely ignored by science educators are embodied in Piagetian theory. The ideas are constructivism, the nature of human knowledge, and learner autonomy.

Purpose

My purpose is twofold. First, the contructivist epistomological position will be delineated in terms of its historical emergence from rationalism, empiricism, and romanticism. Part of the discussion includes an example that clarifies how each epistomology applies the knowing process. Second, a recent body of research on direct teaching will be discussed and interpreted within a constructivist framework. Then, two specific studies will be described in detail, in order to delineate what constitutes constructivism.

Background

The science education community views Piaget primarily as a child psychologist, albeit one who entered the field through the biological sciences. In fact, Piaget's research on the psychogenesis of knowledge represented only a link between two more important areas, the search for adaptative mechanisms in the biological sciences and the epistomological analysis and interpretation of scientific thought, which Piaget viewed as a higher form of adaptation (Piaget, 1977).

Epistomology, the study of the theory and nature of knowledge, emerges as central to Piaget's work. Epistomology is, of course, an area of philosophy, yet the aforementioned error represents a misinterpretation of the epistomological basis, and thus Piaget's theory itself, in science educators' applications of the model to science teaching and learning. Let us therefore remove ourselves from an applied context and inspect the epistomological foundation of the theory.

Piaget viewed science as a means toward an end. Science represented an activity for resolving philosophical problems. Thus, for Piaget, philosophy and science had a special relationship. Great philosophical views of history stem from man's reflections on science or from endeavors that resulted in new sciences. Science thus is led by philosophical considerations. But philosophy is similarly nourished by scientific answers, considered valid by Piaget, because such information is obtained by objective, empirical means. In the process, areas of philosophical study become questions for scientific investigation (Piaget, 1971). Piaget's goal, to obtain scientifically reproducible evidence for a model of the knowing process, seems quite consistent with his perspective on philosophy and science.

To understand constructivism as an epistomological model, it will prove valuable to review briefly a major debate in the history of epistomology. The debate centered on the following question. In what realm does the structure of knowledge lie? Historically, reality consisted of an external, objective dimension and an internal, subjective domain, the object and the subject. At issue was whether our knowledge conformed to objects or whether objects conformed to our knowledge. Rationalist, empiricist, romanticist, and constructivist epistomologies each addressed this issue. The present sketch of the debate is based on a recent paper by Fabricius (1983) who described the philosophical context of Piaget's theory at length, and a book by Gardner (1985) who discussed similar issues in a history of cognitive science.

Rationalism

Fabricius (1983) describes rationalism as the application of mathematical models to philosophy. Rationalism assumed that our knowledge conforms to objects. It flowered on the success of mathematical explanations of natural phenomena. The rationalist movement argued that reality was logical and consistent, and our knowledge of it began with undeniable first premises followed by the deduction of logically consistent conclusions representing facts about the world. First principles were often innate ideas, such as perfection, which was utilized in arguments as evidence for the existence of God. Rationalists generally thought that concepts represented distinctions in reality if they were shown to be clear, self-consistent and distinct from other concepts. Thus, truth was the result of logical deduction, and the objectivity of knowledge was set apart from subjective ideas not logically deducible from first premises.

Perhaps the prototypical rationalist is René Descartes. Gardner (1985) describes how Descartes sequestered himself in a small Bavarian farmhouse to cope with the uncertainly of knowledge. What envolved was a method of systematic doubt in which Descartes questioned all that was not certain. In the end, he was left only with his consciousness and his doubts (Gardner, 1985), represented in his famous statement "I think, therefore I am." These represented the results of his logical argument which established that he could not deny that he thought. Such a denial must necessarily involve thought. Upon this first premise he then searched for knowledge.

Empiricism

Empiricism represented an application of observational and experimental science to philosophy. The empiricists also assumed that our knowledge conformed to objects, but they utilized inductive reasoning from evidence based on experience. They generalized and predicted on the basis of observed facts alone. The sense perceptions were central in knowledge, and the mind began as a tabula rasa prior to experience. Perceptions represented an undistorted, direct picture of the objects and events of reality. Empiricists assumed that all reality was perceived through the senses, and their criterion of truth was verification by experience. Verification was necessary to preserve the objectivity of knowledge against subjectivity, which crept in through distortions or misrepresentations of facts given in the senses.

John Locke was the prototypical empiricist. He challenged the acceptance of knowledge that stemed from introspective evidence, described innate ideas as misleading or useless, and rejected the notion that an idea in one's own mind proved its existence. He argued that our knowledge of the existence of things comes only through sensations and declared that the mind began as a clear state to be filled by experience. Whereas knowledge began with experience and its perception, for Lock it did not end there. His epistomology described a person who reasons and reflects on experience, letting words represent ideas and constructing abstract, general notions from specific ideas (Gardner, 1985).

Hume's Views on Empiricism and Rationalism

David Hume outlined problems of both empiricism and rationalism. Concerning empiricism, he insisted on taking the radical stance that no knowledge exists beyond experience because all knowledge comes from experience. In taking this position, Hume questioned the empiricist account for the structure of knowledge. He argued that knowledge rested on a few basic notions such as causality, the permanence of objects, and the constancy of self. The structure of knowledge is derived from such notions. Within this structure is the comprehension of specific events, facts, and objects. A successful theory of knowledge must explain how such notions are acquired and why they are valid.

Hume went on to argue that in a causal situation the only experience is the conjunction of two objects in space and time. The cause, as such, is not experienced. For example, what is experienced when a moving car collides with one at rest? One car moves toward the other and stops next to it. The car at rest moves away. Our conclusion is that one caused the other to move. Hume argued, however, that we do not have any sensory impression through experience of 'cause'. Concerning objects, Hume maintained that an experience with an object is only a specific set of perceptions. The perceptions themselves do not possess a necessary structure or an object permanence. Regarding self, Hume held that our experience of self is only a series of feelings, thoughts, desires, etc., which are psychic events, not the underlying self. Thus, for Hume, causality, objects, and self represented subjective inputs from the mind that are integrated with experience. Thus, they are not aspects of external reality. Hume's analysis dealt a severe blow to empiricism, because sense perceptions could not account for all aspects of knowledge.

Hume was equally critical of rationalism. He focused on the rationalist attempts to logically deduce knowledge about existence. Mathematical statements, though true, do not necessarily provide knowledge of the real world. For example, the statement, 'all triangles have three sides,' though true, does not mean that triangles exist (Fabricius, 1983). According to Hume, a logical argument from the true proposition to necessary existence is impossible because necessity possesses logical, not existential qualities. In logic, the contrary of a necessary proposition is impossible, but in existence the contrary is always possible. Thus, only the contingency, not the necessity, of existence is possible. In summary, Hume had shown that the structural elements of knowledge were not obtainable through rationalist arguments. Whereas the reasoning may be true, it could not prove that knowledge reflected reality.

The difficulties of 17th- and 18th-century rationalism and empiricism stemmed from the shared aforementioned assumption that knowledge must conform to objects. This postulate was based on a fundamental notion that reality exists as an external dimension of events and objects. The external dimension is objective and separate from our knowledge, the internal dimension, which is subjective. The task of epistomologists who accepted these postulates was to prove how knowledge was based in the external dimension. It remained unfinished, thereby suggesting two conclusions. First, knowledge was not possible. Second, the external objective realm did not contain the structural elements of knowledge. Thus, according to Fabricius (1983), a gap existed between the subject and object, and any knowledge not based in the external realm must be subjective, uncertain information.

Romanticism

Fabricius (1983) states that while epistomological questions were not the primary focus of the romantic philosopher, Jean-Jacques Rousseau, his philosophy contained a radical perspective, one pertinent to the subject-object gap. Rousseau argued that knowledge was based internally, in a primary, natural process that controlled feelings. This view was founded on the fact that the deepest feelings seem present in all societies and naturally acquired. Thus, the epistomological task that faced rationalism and empiricism evaporated. For Rousseau, the structural elements of knowledge were within. One need only examine the internal dimension to find them.

Conflicts exist, however, in Rousseau's internal reference and his acceptance, according to Fabricius (1983), of the assumption that knowledge conforms to objects. Rousseau also accepted the notion that one's natural feelings coincided with the structure of external reality. Whereas one can assume that what is felt internally exists internally, can one assume that what is felt exists externally? Thus, Rousseau's argument is not only subjective, but also open to the challenge that internal feelings cannot prove external existence.

Constructivism

The subject-object gap remained as epistomologists attempted to demonstrate how the structural elements of knowledge could be shared by the external and internal dimensions of reality. Regardless of their position, the structural elements of knowledge must interact with the other dimension.

The German philosopher Immanuel Kant addressed the gap in Critique of Pure Reason, first published in 1781. His purpose was a synthesis of the rationalist and empiricist viewpoints. Gardner (1985) describes clearly the task, . . . "he had to confront the question whether there might exist knowledge that is necessarily so - hence, a priori - but is also in some sense dependent on experience, not just conjured up tautologically in the mind" (p. 57). In carrying out the task, Kant employed rationalist logic to analyze the often idiosyncratic nature of experience. His analysis focused on what permitted the mind to assimilate experience, as it does, and to produce necessary knowledge.

In rationalist tradition, Kant accepted only his own awareness and judgment, called ego or transcendental self. He viewed the mind as an active agent, one that organizes and coordinates experiences. Such activity somehow transforms the chaos, multiplicity, and redundancy of experience into an ordered wholeness of thought. Moreover, the entire process is subject to internal rules integral to the mind's operation. Thus, the self depends upon and is stimulated by the external realm, but it can only understand the external realm though appearance. And appearances are shaped by the internal rules, the mental structures of the active self. (Gardner, 1985).

Kant had invented a phenomenal dimension, a third layer of reality. The structural elements of knowledge lie there, and their function is to interact with the internal and external dimensions. Gardner (1985) writes that one must always deal with phenomena, the appearance of the external realm, rather than with noumena, the unknowable external world. These phenomena are sensations caused by external objects. But the form of phenomena is due to the structures that mold it. And for Kant the two most fundamental structures are space and time. Kant, like Hume, maintained that one does not experience what couples separate perceptions, for example "red and spherical." However, he went beyond Hume and located our knowledge of objects, for example a red ball, in the mind's structures of space and time.

Beyond space and time, according to Kant, the mind imposes certain a priori, abstract categories on experience. Objects perceived in space and time are understood through such categories as quantity, quality, relation, and modality. Finally, Kant contended that the unity of the known and the possibility of awareness of self are imposed by the mind on experience during thought. These make up the mental apparatus the mind uses to organize experience and construct knowledge.

Set between the perceptions and the abstract, a priori categories set forth by Kant are schemas. Schemas are mediating representations, partly intellectual and partly sensory, which provide an interpretation of experience. Schemas are part rule and part image, in that they link understanding and perception. Within a certain category, its schemas determine the nature of the category's application to experience. For example number is the schema for the category called quantity, permanence in time for relation, etc. (Gardner, 1985). Schemas are also present at the level of concrete experience. I employ the concept 'cat' to my cat, Mischief, thereby representing the concept and distinguishing between the representation or schema and the concept itself. Kant's invention of a third layer of reality let him assume that objects conform to the structural elements of knowledge, which lie in the phenomenal realm. Kant's reversal of the older view, that our knowledge must conform to objects, revolutionized epistomology in a manner similar to Copernicus in astronomy.

Fabricius (1983) employs an example of common experience and draws an anology to clarify Kant's conception of the phenomenal realm. Suppose that one goes to a gravel pit to get stones for a driveway. All stones have been separated in advance by an employee using a 1/4-inch square screen. All stones which passed through the screen have been piled separately from larger stones. Upon examination of the pile of small stones, several lines of thought are possible. Empirical observation suggests that all stones in the pile must be the size of those observed. Or, one might rationally reason that some inherent logic exists in the homogeneous size of the stones. Romantically, one may conclude from immediate feelings that this is the right pile of stones for the driveway. Each perspective, however, ignores the structuring function of the screen. If one knows the role of the screen in organizing the experience, then certainly is assured. The screen is analogous to the phenomenal dimension. Its location is new, and it plays an inherently active role in the experience with the pile of stones. Fabricius (1983) writes, "Before Kant...it had been the purpose of epistomology to explain how the subject did not interfere with the object when coming to know it. Until

Kant, only subjective ideas could result if the mind added anything to the object. But Kant proposed that this is in fact what always happens, and that it is the universality of what the mind does to construct phenomena that gives knowledge its objectivity" (p.322).

Kant and Piaget share much in common beginning with the different levels on which analysis occurs. Kant's sensory world, abstract, a priori categories, and interposing schema parallel Piaget's content, function, and structure. Content is the raw, uninterpreted behavioral data. Function represents the broad, universal aspects of intelligent activity which Piaget described in terms borrowed from biology. Function is Piaget's mechanism of assimilation, accommodation, and adaptation (also called equilibration and self-regulation). Structure is interposed between function and content, and changes with age. Structures are the organizing properties of intellect, which are constructed by function itself and identifiable from content or behavior. (Flavell, 1963).

Their active, constructivist views of knowing share additional common ground. For both, the concept of object is located in the structures of the mind. For Piaget, these structures are schema which coordinate the infant's earlist actions and themselves are coordinated into the scheme of the permanent object. Piaget's intellectual operations, which emerge later, are analogous to Kant's categories of understanding. Both provide relations that one employs to know. These mental structures are ordering, coordinating and synthesizing prinicples. They can be identified only after they are used on experiences. The consciousness of self and its differentiation from the external dimension rests upon constructive activity by the knower. Therefore, the interactive role of the structural elements of knowledge reveals their constructive function, to order coordinate and synthesize sensory inputs. For Kant and Piaget, reality becomes the phenomena we experience through construction (Fabricius, 1983).

Kant and Piaget are distinguished by their views on a priori knowledge. Kant's categories are a priori, whereas Piaget's intellectual operations, particularly those connected with formal thought, are not. Thus, Kant and Piaget differ on the temporal nature of knowledge. Kant, like those before him, assumed an atemporal notion. Piaget, however, incorporates time in his equilibration mechanism, because the mental schema develop over time via equilibration. Piaget's temporal notion of knowledge permits a circumvention of the problems of Kant's epistomology. Dramatic achievements in physics have modified our understanding of nature and, for example, refuted Kant's assumption regarding the given nature of space and time.

In summary, Fabricius (1983) points out that modern epistomology must address the issue of time to understand its necessity in knowledge. Yet, in this quest, it must be remembered that knowledge within the phenomenal realm is delimited by its mental structures in determining the ultimate nature of reality. Similarly modern science education must reconcile the issue of time in Piaget's theory. Knowledge, or reality, for the subject changes gradually over time via the equilibration process, and Piaget's (1971) position is that reality is neither external and ready-made nor innate and predetermined. Rather, truth lies between these extremes and is acquired through the constant constructive activity of the subject, which produces new, more sophisticated mental schema.

Implications for Science Teaching and Learning

Implications of Piaget's epistomology for science teaching and learning stem from the concepts of time, constructivism, and mental schema. They may be developed as questions. First, given that the structural elements of knowledge exist in a phenomenal realm as mental structures that develop over time and through an internal constructive process, then how should science be taught so as to encourage knowledge construction in learners. Second, if learners must construct knowledge only from current knowledge, already operative schema, the constructive process, and experience, then what factors influence the construction of knowledge by learners.

Lawson (1985) and Staver (1984) recently have discussed much of the research that surrounds both questions. In the remainder of this paper, the epistomological theme is continued by discussing Piaget's views on the kinds of knowledge. This issue was taken up briefly in an earlier paper (Staver, 1984) and is relevant to the above mentioned questions because the kind of knowledge and the method of teaching it are frequently confused.

Knowledge is often described in terms of its source in Piaget's theory. Physical knowledge, often called exogenous knowledge by Piaget, is illustrated by the size, shape, weight, and color of any object, such as a ball. The source of physical knowledge is our direct experiences with external objects or the material results of a person's actions on objects (Piaget, 1977). For example, one need only to observe directly that one marble is lighter than a second or that one ring rolls faster down a hill than another.

The fact that the small, spherical object mentioned in the previous paragraph is called "ball" is an example of social, sometimes called conventional, knowledge. The source of social knowledge lies in conventions established by people, and children communicate with others to acquire social knowledge.

Logico-mathematical knowledge, often called endogenous by Piaget, may be illustrated by an example of three balls, each with a different weight. Suppose a child observes the weighing of three balls, A,B,C, as follows: A and B are weighted, and $A<B$. Then A is removed from sight, and B and C are weighed, with $B<C$. What is the relation of A to C? Whereas the individual weighings and the results that $A<B$ and $B<C$ represent physical knowledge, the knowledge that $A<C$ introduces a new category, one that may be experientially based, but one that requires an internal coordination of the subject's actions or operations. Piaget (1977) maintained that "the distinctive character of endogenous knowledge is thus its necessity as opposed to the simple matters of fact that exogenous knowledge records" (p. 804).

By focusing on the movement of children through Piaget's stages, psychologists and science educators not only ignored constructivism, the nature of human knowledge, and learner autonomy, they applied Piagetian theory from an empiricist perspective. But research results, negative and positive, focusing on the stage concept have reaped a great harvest for science teaching and learning. On the negative side, we know more about what does and does not constitute constructivism (Siegler, Liebert, & Liebert, 1973; Greenbowe, Herron, Lucas, Nurrenbern, Staver, & Ward, 1981). On the positive side, we know much about the influence of reasoning in understanding science concepts, particularly from the writing of workers who understood and applied properly the constructivist nature of Piaget's theory (cf. Herron, 1975).

Two misguided scenarios, however, stem from our lack of attention to constuctivist epistomology and the nature of knowledge as well as our preoccupation with the stage concept. First, science teachers often have selected instructional methods that are inappropriate to the kind of knowledge taught. For example, science teachers often use direct methods, which emphasize direct transmission, in teaching science concepts whose nature is logico-mathematical rather than social. Logico-mathematical concepts require internal coordinations of actions or operations, construction within; thus, teachers must design activities that permit students to actively construct logico-mathematical concepts. Such activities should include inquiry, concrete models and materials, and discussion among students during instruction.

Though not heavily researched in science eduction, direct methods, often called 'effective teaching' in the literature (Rosenshine, 1986), are quite effective for teaching explicit facts, concepts, and skills in reading and mathematics. The effective teaching pattern includes the presentation of material in small steps, frequent pauses and checks for student understanding, and active, successful participation by all learners. (From here on 'effective teaching' refers to the direct methods.)

Rosenshine (1986) maintains that the results of effective teaching research apply...."to the teaching of mathematical procedures and computations, reading decoding, explicit reading procedures such as distinguishing fact from opinion, science facts and concepts, social studies facts and concepts, map skills, grammatical concepts and rules, and foreign language vocabulary and grammar" (p. 60). Rosenshine (1986) further suggests that limits exist for the application of effective teaching methods. "These findings are less relevant for teaching in areas less well structured, that is where skills do not follow explicit steps or the concepts are fuzzier and entangled" (p. 60). Examples are teaching composition and analyzing literature, and teaching entangled concepts such as "liberal" or "modernism" (Rosenshine, 1986).

One area of success and limitation for effective teaching is concept learning. Rosenshine suggests that an important factor is the explicit or implicit nature of the concept. But, concept learning is largely a matter of classification. Bybee and Sund (1984) describe classification as the ability to identify syemmetrical relations among things, to catergorize objects that belong together. But, in Piagetion theory classification can be accomplished by a child using preoperational, concrete operational, or formal operational thought. Classification for the preoperational child is a perceptual activity. For example, the child sees several red blocks and places them together. In concrete operations, the child develops the capacity to sort through a multicolored pile of blocks, make a separate pile for each color, and explain how this is done (Bybee & Sund, 1984). But formal thought is required to arrange groups in a multilevel hierarchy, particularly when intangible, abstract properties are involved. For example developing a phylogeny or distinguishing between oxidation and reduction as chemical processes require formal thought (Karplus, et al., 1977).

Thus, what Rosenshine views as explicit or implicit concept learning, I see as concept learning that requires preoperational, concrete, or formal thought. This is precisely the major result of much of the stage concept research. Though concept learning is a matter of classification, a wide range of reasoning may be necessary to understand a concept, depending on its concrete or abstract characterisitics, or its explicit or implicit nature to use Rosenshine's terms. Herron (1975) has clearly and frequently delineated this issue with specific examples in chemistry.

Direct methods do, however, have an important place in science teaching. First, they are quite appropriate for the transmission of social and conventional knowledge. Second, direct methods are relevant for the abundance of physical knowledge in science which can be acquired through observation and practice. Such knowledge does not require students to construct entirely new schemas or to modify radically ones that already exist. Thus, active construction occurs readily, although it appears that knowledge is transmitted in empiricist fashion.

An Instance of Confusion

Many science educators, myself included, have been critical of direct methods. First, such methods are not the most effective for students' construction of implicit concepts and skills, which are logico-mathematical in nature, for example problem solving. Second, when applied in such areas, these methods seem to promote rote learning of facts and rules that do not transfer well to new situations. They also seem derived from an empiricist epistomology. Piaget's goal for education was an automous learner, one who could use generalized intellectual skills and knowledge in new situations.

Numerous confusing arguements and examples exist in the literature, but one in particular has been chosen for discussion because the issue seems clear, and I was involved in resolving it. Siegler, Liebert, and Liebert

(1973) reported a study in which they successfully trained 10-and 11-year old learners to solve Inhelder and Piaget's (1958) peudulum problem in a single, 30-minute intervention session. They write, "The control group results supported Inhelder and Piaget's (1958) observation that unaided 10-and 11-year olds do not grasp quickly the strategy required to solve the pendulum problem. However, those authors' proposed explanation in terms of cognitive unreadiness appears inadequate; given appropriate instruction, preadolescent individuals clearly are capable of separating the effects of weight and length and of determining which of the two affects a string's rate of movement" (Siegler, Liebert, & Liebert, 1973. p. 101).

The schema necessary to solve the pendelum problem is control of variables reasoning. Inhelder and Piaget's position is that most preodolescents do not yet possess this schema which is a characteristic of formal thought. Siegler, Liebert, and Liebert's position is that it can be successfully taught in a specific problem. At issue is what is being taught. Piaget's position is that such schema are acquired through the contructive process, do not emerge quickly, and when present are usable in a wide variety of problems. Siegler's position is that students can benefit from appropriate instruction on a specific problem, although they are not developmentally ready.

Siegler's brief intervention contained many components of what has been described earlier as effective teaching. For example, a general conceptual framework for viewing a problem was presented. This was followed by the guided solution of two problems that required similar solution strategies but contained content unrelated to the pendulum problem. Finally, students were trained to use a stopwatch, told that the conceptual framework already presented applied to the pendulum problem, and instructed to solve the pendulum problem. The experimenter manipulated the pendulum and the student was provided a data sheet organized such that he/she could enter data in prepared blanks. The conceptual framework included definitions of the terms "dimension" and "level" followed by the presentation of a rule to link the two terms. Specifically, the rule stated, "If one level of the dimension is always higher on the measure than the other level, then that is the important dimension" (p. 99).

Did Siegler's intervention allow his subjects to construct, use and retain the control of variables schema? Or, did the training only provide them with a simple rule to memorize and follow in known applicable situations? If the first question can be answered in the affirmative, then the entire concept of developmental readiness must be questioned. An affirmative answer to the second question does not contradict Piaget's theory, but instead exemplifies much learning that takes place in schools; student memorize rules and learn to apply them in closely related situations. Important educational implications exist if Siegler's brief intervention can produce the lasting behavior described by Inhelder and Piaget (1958). If, however, such training yields successful performance on specific, similar problems presented in the same manner, then the finding is inconsequential. That students have been trained successfully to solve problems with algorithms is well known.

A group of science educators (Greenbowe, Herron, Lucas, Nurrenbern, Staver, & Ward, 1981) replicated and extended Siegler's original experiment with the purpose of answering the developmental readiness question. In the course of planning the replication, we found several important differences between the Inhelder and Piaget (1958) pendulum task and Siegler's pendulum problem. First, the Inhelder and Piaget task was far less structured than was Siegler's problem. With the former, the subject must decide without aid how to solve the task. This includes identifying the variables present, manipulating them individually, checking all possibilities, and realizing the logical necessity that all other variables must be held constant. Moreover, it is this thought process, not the answer itself, that represents this formal schema for Inhedler and Piaget. Siegler's version was limited to two variables, and all manipluations were done for the subject. The possiblity exists that subjects could identify the important factor in pendulum motion without going through the thought processes required in the Inhelder and Piaget version.

Our replication study added transfer and delayed postests to evaluate the retention and transfer characteristics of the intervention. The immediate posttest was the Siegler version. The transfer task was the rolling balls problem (Howe and Mierzwa, 1977; Wollman, 1977). The delayed posttest, administered two weeks later, was the Inhelder and Piaget version of the pendulum problem. The results are as follows. Siegler's intervention effect was replicated on the immediate posttest. However, the transfer effect was weak, at best, and there was no evidence of a retention effect after two weeks. Our conclusion is that Siegler's treatment did not facilitate the construction of the control of variables schema by his subjects, but was rather an instance of successful algorithm learning.

Thus, we return to the question, what is taught? If students are to learn new logico-mathematical knowledge, then substantial restructuring of existing schema or building of new schema is in order. The active construction of such schema will require time and instruction appropriate to the knowledge. Such instruction should emphasize discovery rather than direct methods.

A Concluding Thought

The goal of this paper was to sketch the epistomological roots of contructivism, to clarify certain implications for science education, and to explicate the issues surrounding a specific research study and its replication. In conclusion, a single point must be emphasized. First, the goals for United States science education in the 1980s, outlined in a recent National Science Teachers Association (1982) position statement, stress citizen scientific literacy. Careful inspection of the NSTA's attributes of a scientifically literate individual suggests that such a person is an autonomous learner. The production of autonomous learners was one of Piaget's primary goals for education. It seems clear that an autonomous learner needs physical, conventional, and logico-mathematical knowledge, particulary the kinds of mental schema named in the introduction. It also seems clear that discovery methods, for example the learning cycle, foster the construction of logico-mathematical knowledge better than do more direct methods. Thus, science educators must continue to demonstrate that science taught as a process of finding knowledge fosters the most fundamental aspect of American democracy, an informed, literate citizenry.

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